

SAR Remote Sensing of Nonlinear Internal Waves in the South China Sea

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LONG-TERM GOAL

To understand the environmental effects (e.g. bottom topography, shoaling, mixing, and current/shear) on nonlinear internal wave generation, evolution, and dissipation in the South China Sea by using satellite synthetic aperture radar (SAR) imagery, in-situ data, and numerical models.

OBJECTIVES

The objective of this study is focused on observations and analysis of nonlinear internal waves and mesoscale features (e. g. eddies, fronts) in the shelf-break region of the South China Sea. The task is concentrated on the collection and analysis of SAR imagery (ERS-2, ENVISAT ASAR, and RADARSAT ScanSAR) and mooring data from field experiments in the South China Sea. Of particular interest is the generation of huge internal waves caused by the branch out of Kuroshio through Luzon Strait and its evolution and dissipation on the shelf break.

APPROACH

The approach is to use the SAR data in conjunction with the in-situ measurements from field experiments to calibrate and validate SAR imaging mechanism of nonlinear internal waves, and to integrate all data by wave model for data assimilation. A validated and calibrated algorithm and model can be very useful for the understanding of shelf processes and for the applications of internal wave effects on acoustic propagation. A parametric study for various environmental conditions will be carried out to demonstrate and assess the nonlinear effects such as bottom topography (across critical depth), shoaling, stratification, and dissipation. The generation and evolution of internal waves (elevation versus depression, and mode-one versus mode-two), and wave-wave interaction will be studied using satellite data in conjunction with in-situ data from the field experiments. Key collaborators of this project are Dr. Antony Liu at NASA Goddard Space Flight Center, currently detailed at ONR Global –Asia, and Prof. Ming-Kuang Hsu at Northern Taiwan Institute of Science and Technology, Taiwan.

WORK COMPLETED

During this report period, in collaboration with Dr. Antony Liu at ONRG-Asia and Prof. Ming-Kuang Hsu from Taiwan, several dozens of SAR images from ERS-2, ENVISAT ASAR, and RADARSAT ScanSAR from 2003 – 2005 were processed and analyzed for nonlinear internal waves study in the South China Sea. The internal wave packets in Babuyan Channel off the Northern coast of Luzon of

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Philippine propagating either east toward the Philippine Sea or west toward the SCS were observed in ENVISAT SAR images on April 7 and May 7, 2004. These internal wave packets are probably the ones closest to the islands in the Luzon Strait found so far from SAR images. Their possible origins and evolutions were studied. Taking the advantage of the 30 minute acquisition time offset between ERS-2 and ENVISAT SAR and their almost exactly same path, the evolutions of ocean features (such as internal waves, fronts, eddies, typhoon...) can be observed and tracked through sequential SAR images obtained respectively from these two satellites. A case study for deriving ocean surface drift by wavelet analysis from two sequential SAR images, one from ERS-2 and another from ENVISAT, over the southern part of Luzon Strait near Philippines on April 27, 2005 was carried out. A newsletter reporting the results of this case study was written and published jointly with Dr. Liu and Prof. Hsu. An oral presentation was given at AGU Western Pacific Geophysics Meeting in Beijing, China on 24-27 July 2006.

RESULTS

1) Locally Generated Internal Wave Packets in Babuyan Channel Observed from SAR Images

Previous studies of satellite remote sensing data and field measurements have revealed that nonlinear internal waves are very active in the north of South China Sea (SCS). For example, from hundreds of ERS-1/2, RADARSAT and Space Shuttle SAR images from 1993 to 2000, Liu and Hsu (2004) has compiled the internal wave distribution map in the north of SCS including Hainan Island coast. Mooring measurements collected during ASIAEX field experiments have also showed both mode-one and mode-two internal waves in the SCS. Based on the internal wave distribution map, most of the internal waves in the northeast part of South China Sea are propagating westward. It is believed that Luzon Strait is the generation source of most of nonlinear internal waves in the north of SCS. From the observations at drilling rigs near Dongsha Island by Amoco Production Co. (Bole et al., 1994), the solitons may be generated in a 4 km wide channel between Batan and Sabtang islands in Luzon Strait. The sill between Batan and Sabtang islands is like a saddle point. The proposed generation mechanism is similar to the lee wave formation from a shallow topography in the Sulu Sea (Liu et. al, 1985). The disturbance of mixed area with downward displacement of the pycnocline is then driven by the semi-diurnal tide and evolves into a rank-ordered wave packet. However, all internal waves captured in the SAR images and shown in the distribution map are not in a close distance to the channels between Batan and Sabtang or other islands in the Luzon Strait. This makes it difficult to identify the exact generation locations of the internal waves observed in the SCS. Therefore, SAR images capturing internal waves in a close distance to the channels of Luzon Strait is desirable for identifying the exact generation locations of internal waves in the SCS and testing the proposed internal wave generation theory in the SCS.

Our study of several dozens of SAR images from ERS-2, ENVISAT, and RADARSAT from 2003 to 2005 has led to the discovery of such images. ENVISAT ASAR Wide Swath images on both April 7, 2004, and May 7, 2004, have captured the internal waves in the Babuyan Channel off the northern coast of Luzon of Philippine as shown in Figures 1 and 2. These internal wave packets are probably the ones closest to the islands in the Luzon Strait found so far from SAR images. The Babuyan Channel has its shallowest place west to the Fuga Island as shown in Figure 3. The main internal wave packet captured on the image of April 7, 2004 is in the middle of the channel near the Municipality of Aparri and east to the shallowest place of the channel, and is propagating east toward Philippine Sea, while the internal wave packet on the image of May 7, 2004 is closer and west to the shallowest place of the channel, and is propagating west toward the SCS. Since the distances between the leading and the

second solitons on both images are small, especially on the image of May 7, 2004, these internal waves are generated locally. From the propagation directions of these two internal wave packets, one can see that the generation source of the main internal wave packet on April 7, 2004 must be in the west of its location, while the generation source of the one in May 7, 2004 must be in the east of its location. Given the locations of these two internal wave packets and the facts that the shallowest place in Babuyan Channel is only 290m deep, its west side depth increases rapidly to over 2000m, and its east side depth increases rapidly to 500m and then eventually to over 2000m, the shallowest place in the Babuyan Channel is probably the generation place of these two internal wave packets. This conclusion is in agreement with the fact that the distance between the leading and the second solitons in the image of April 7, 2004 is larger than the one in the image of May 7, 2004 which suggests that the generation source is closer to the location of the internal wave packet shown in the image of May 7, 2004. Thus SAR images such as Figures 1 and 2 can help pinpoint the generation sources of internal waves in the Luzon Strait.

Recent work by Liu and Hsu (2003) has suggested that the long-crested internal waves near Luzon Strait are produced by the connection along the crest of many individual wave packets generated from different sources or sills in the strait, the so-called "Hand-in-Hand" phenomenon from multiple sources (Hsu and Liu, 2003). Therefore, discovering all potential generation locations of internal waves in the Luzon Strait is important for testing this and other proposed generation theories of internal waves in SCS.

SAR images from ERS-2, ENVISAT, and RADARSAT from 2003 to 2005 have also confirmed that the internal waves are very active in the SCS and the most internal waves in the northeast part of South China Sea are propagating westward as reported in the studies of Liu and Hsu (2004) and others.

2) Ocean Surface Drift Derived by Feature Tracking Between ERS-2 and ENVISAT SAR Images

Sequential satellite images of ocean surface within a feature's coherent time period from a single satellite sensor have long been used to observe and track the evolutions of some ocean surface features. For example, the data from SSM/I, NSCAT, QuikSCAT, and AMSR-E have been used to derive sea ice motion data in both the Arctic and the Antarctic regions (Liu and Cavalieri, 1998a; Liu et al., 1999; and Zhao and Liu, 2002). However, for tracking the evolutions of the ocean surface feature that have very short coherent time periods, such as deriving ocean surface drift, both the spatial and temporal resolutions of the satellite images must be very high since the temporal resolutions must be within the coherent time periods of the surface features and the spatial resolutions must be fine enough to detect the motion of the features. Satellite images from a single satellite sensor currently in orbit is either not having fine enough spatial resolution or not having fine enough temporal resolution for such applications. Fortunately, at present, there are two SAR sensors on different satellites, ERS-2 and ENVISAT, having acquisition time offset around 30 minutes and spatial resolution 25 m with almost the exactly same path. This enables us to observe and track the evolutions of ocean surface features that have about 30 minute and longer coherent time periods by using pairs of sequential SAR images obtained respectively from ERS-2 and ENVISAT. The challenges of this approach include co-registering the images and identifying the same features in the sequential satellite images that are obtained from sensors in different satellite.

As a case study on deriving ocean surface drift from sequential images obtained respectively from ERS-2 and ENVISAT, SAR data from ENVISAT and ERS-2 were collected on April 27, 2005 at

01:54 and 02:22 GMT, respectively, over the southern part of Luzon Strait near Philippines. The two images were first co-registered by mapping both of them to the longitude x latitude coordinate system with same pixel sizes $0.0005^\circ \times 0.0005^\circ$ (about 55m x 55 m). Figure 4 shows the remapped ERS-2 60 km x 80 km SAR image obtained on April 27, 2005, north of Philippines in the Luzon Strait, and the location map with the SAR image coverage area shown in the big box for reference. A chain of islands in the Luzon Strait can be easily identified in the SAR image. Also, a big eddy (on the east of islands), oil slick (on the west of islands), wave refraction, and fronts around these islands are clearly observed in SAR image as the mesoscale surface features. For further detailed study, a SAR subscene was selected from each image. Figure 5 shows the overlaid of these two SAR subscenes of ERS-2 in green and ENVISAT in red. The central location of these subscenes is 21.15°N and 121.68°E , and the size is approximately 28.2 km x 28.2 km. The subscene coverage area is shown in the small green box in Figure 4. The major oceanographic feature, a long oil slick oriented in north-south direction, can be clearly identified. The phase shift of this oil slick in 28 minutes shows the surface drift pattern due to the advection of surface current.

To derive the surface drift, a two-dimensional Gaussian wavelet (often referred to as a "Mexican hat" wavelet) transform was applied to the selected SAR subscenes to filter out the uninterested features. Wavelet transforms are analogous to Fourier transform but are localized both in frequency and time. A two-dimensional wavelet transform is a highly efficient band-pass data filter, which can be used to separate various scales of processes. This is critical since the use of two sensors from different satellites will have quite different dynamic ranges of data, and the filtered data with the same dynamic range are essential for feature tracking. Then the filtered images, acquired 28 minutes apart, were examined to find matching features using templates and the results were then converted to motion vectors. The two-dimensional Mexican hat wavelet has been applied to satellite images to separate processes at various scales, including relative phase/location information for coastal monitoring applications (Liu et al., 1997a), and for ice edge and ice floe tracking (Liu et al., 1997b). It can also be used for separating texture or features; for near real-time "quick look" analyses of satellite data for feature detection; and for data reduction using a binary image.

Figure 6 shows the surface drift (green arrows) derived by the wavelet analysis method from the two selected subscenes of ERS-2 SAR and ENVISAT ASAR surface roughness backscattering data. The subscene of ENVISAT image appears as background to highlight the oil slick. As shown in this figure, the oil slick motion of 1.2 m/s at maximum by surface current advection has been well derived and can be clearly identified. Notice that the converging area at the top showing a kink on the oil slick. Also, the shear zone in the middle dilutes and bends the slick near the bottom. Furthermore, on the right-hand side of slick, a small eddy of 10 km size can be identified from their cyclonic circulation flow pattern. The areas lacking drift vectors in the map indicate the regions where filtered features were not matched.

To validate the results, wind data from QuikSCAT are compared with the satellite-derived flow field. The SeaWinds instrument on the QuikSCAT satellite is a specialized microwave radar that measures near-surface wind speed and direction under all weather and cloud conditions over Earth's oceans. The wind map has been distributed with a 25 km grid over the ocean surface. In this study geographical location, three wind vectors have been identified as red arrows in Figure 6. The wind speeds and directions for the three wind vectors in Figure 6 from left to right are listed as follows: (a) 5.74 m/s, 198.5° ; (b) 5.18 m/s, 193° ; and (c). 3.4 m/s, 297.2° , where the wind direction of 0 degree implies a flow toward the north. So, the wind vectors (a) and (b) having a speed of 5 to 6 m/s are coming approximately from the North and that is probably why the oil slick is more or less north-south

oriented originally. The wind on the right-hand side is relatively weak (3.4 m/s) and coming approximately from the East. Although the wind data are very limited, the comparison shows a qualitatively consistent pattern between wind data and SAR observation, especially for the oil slick feature. These results indicate that multiple SAR images overlapped in a short time can be used to derive ocean surface drift, and can help to identify oceanic processes such as currents and eddies. Since there are no in-situ measurements or drifter buoy data in this Philippines coast water, further validation and calibration are definitely warranted for future study. The surface drift pattern derived from satellites can be very useful to study the sources of internal wave generation area.

3) Detecting a Mysterious Ship Near Another Big Eddy from ERS-2 and ENVISAT SAR Image

Ship and their wakes can be detected in the high-resolution SAR imagery provided by satellites. In general, ship is a very effective corner reflector, so ship can be easily observed as a bright spot in the SAR image. But, occasionally, the ship in the SAR image remains invisible, and only trailing dark turbulent wakes are seen (Liu et al., 1996). Figure 7 shows ENVISAT and ERS-2 28 km x 28 km SAR subscenes from the image collected on April 27, 2005 north of Philippines in the Luzon Strait (next scene from Figure 4) with a big eddy. The subscenes cover the area from latitude of 20.61° to 20.86°, and longitude of 122.09° to 122.34°. The invisible ship and its wake in the boxes near the eddy can be tracked easily in these figures. Then, the ship speed is estimated from the distance between ship locations in each SAR image and SAR acquisition time interval (28 minutes) to be 5.94 m/s. Very low backscattering of the ship configuration may have hidden the invisible ship from view, or the wake could have been formed, instead, by an underwater vehicle.

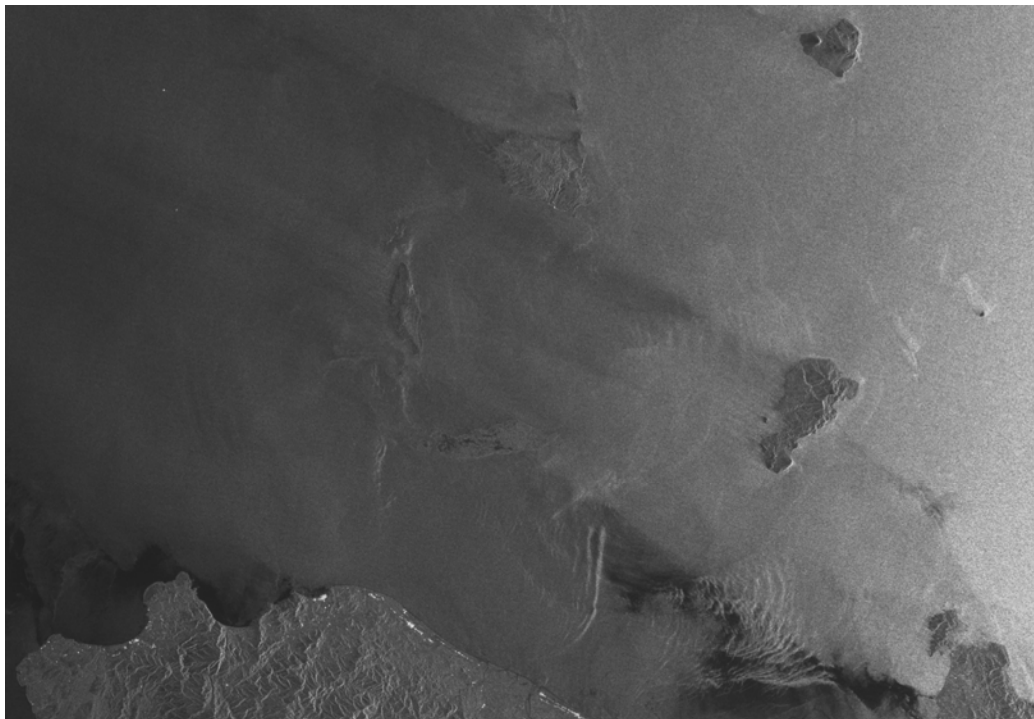


Figure 1. Subscene of Envisat ASAR Wide Swath image (copyright ESA 2004) collected over the North of the South China Sea on April 7, 2004, showing an internal wave packet in the Babuyan Channel off the northern coast of Luzon of Philippine that propagates east toward the Philippine Sea.

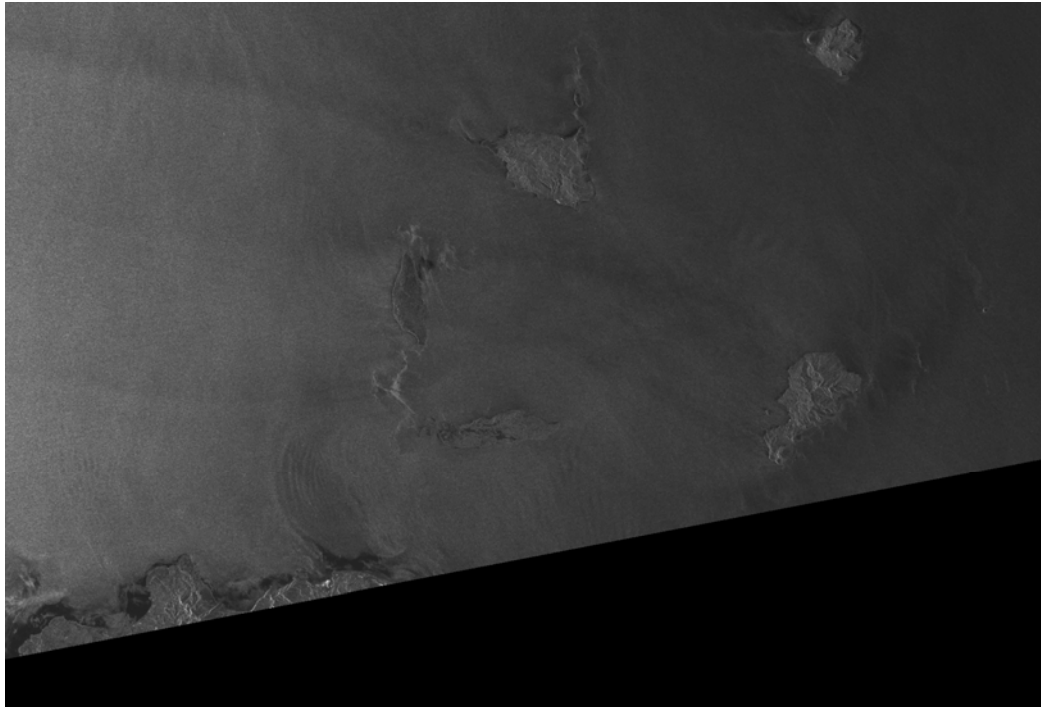


Figure 2. Subscene of Envisat ASAR Wide Swath image (copyright ESA 2004) collected over the North of the South China Sea on May 7, 2004, showing an internal wave packet in the west end of Babuyan Channel off the Luzon coast of Philippine that propagates west toward SCS.



Figure 3. Bathymetry of the southern part of Luzon Strait.

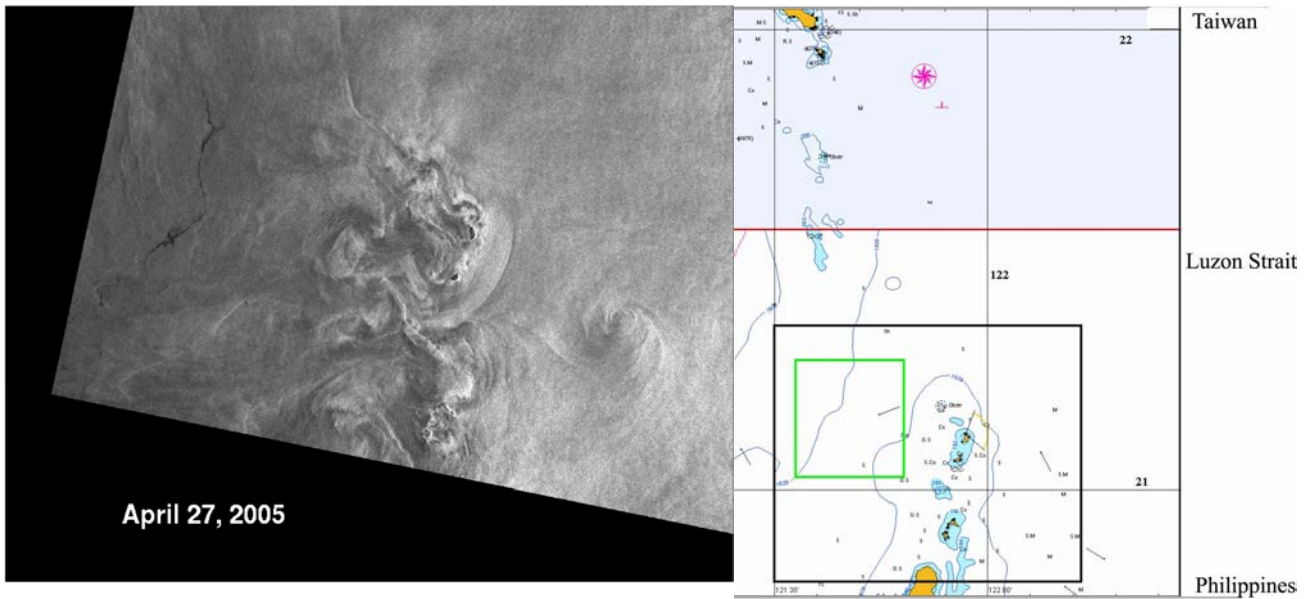


Figure 4. (a) ERS-2 60 km x 80 km SAR image (copyright ESA 2005) obtained on April 27, 2005, north of Philippines in the Luzon Strait, and (b) the location map with the SAR image coverage area shown in the large box.

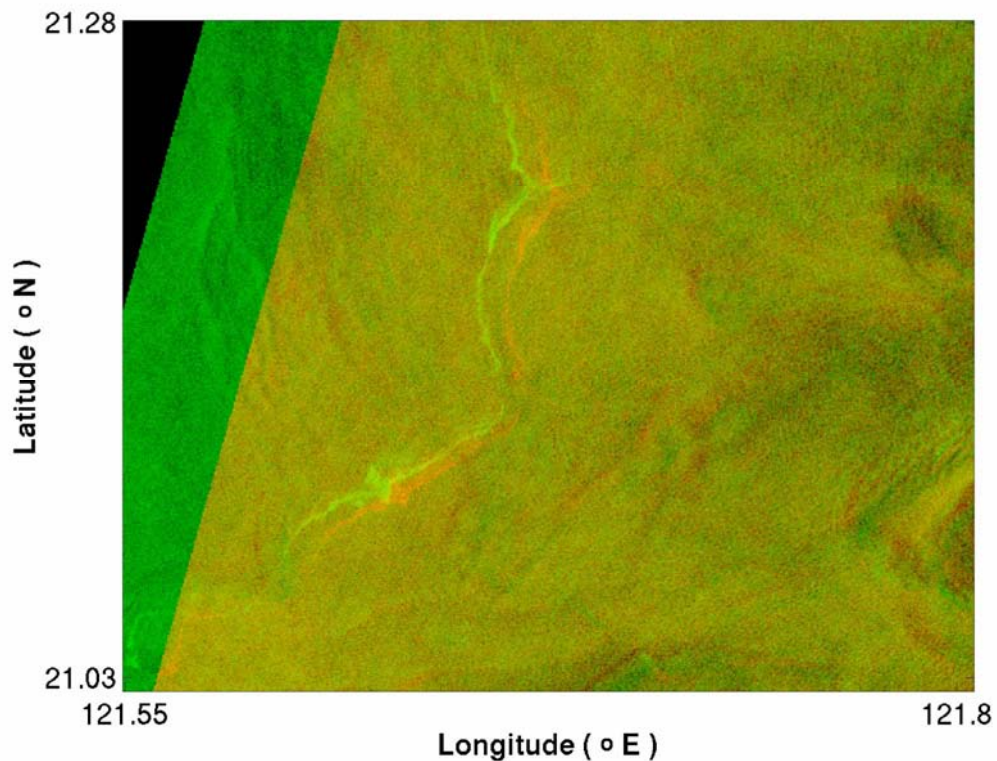


Figure 5. Overlaid of two SAR subscenes collected over the Luzon Strait near Philippines from ERS-2 (in green), and ENVISAT (in red) on April 27, 2005 separated by 28 minutes. The subscene coverage area is shown in the small green box in Fig. 4(b).

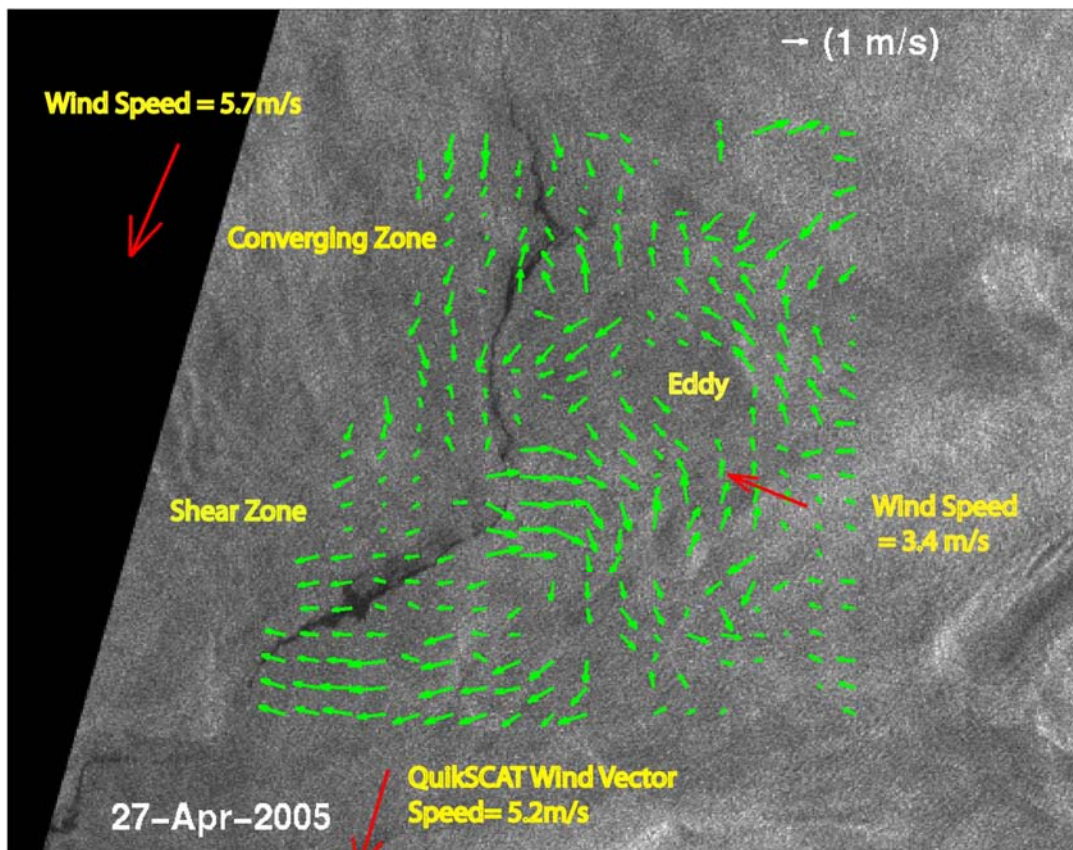


Figure 6. Ocean surface drift (green arrows) derived from ERS-2 and ENVISAT SAR data over the Luzon Strait (ENVISAT image as background). The surface drift unit of 1 m/s is indicated by a white arrow at the top. The QuikSCAT wind data are shown as red arrows.

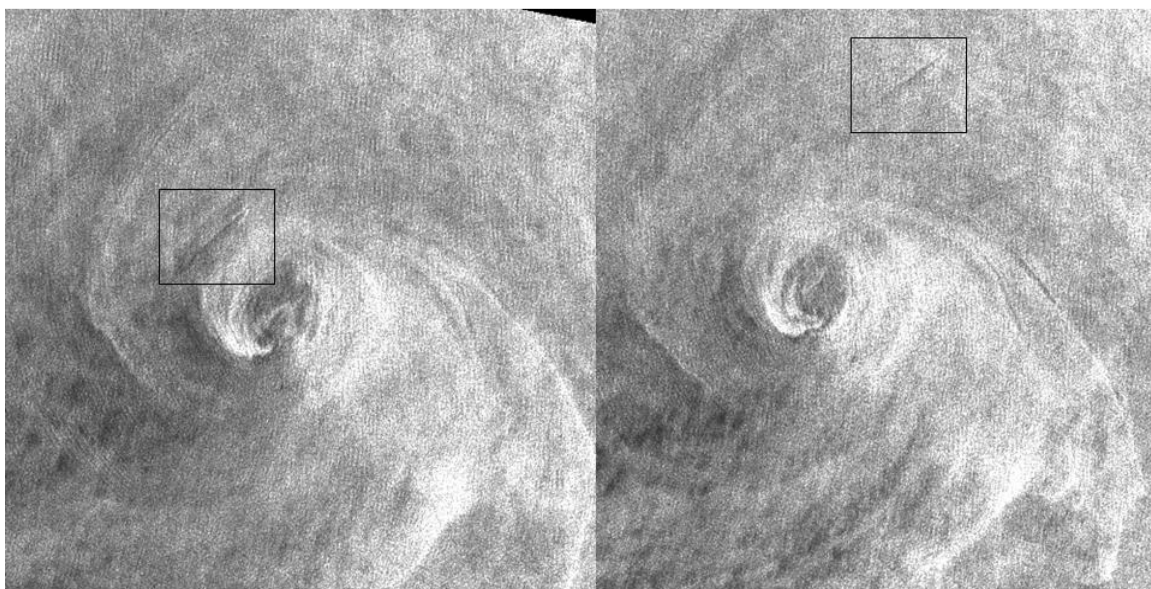


Figure 7. ENVISAT and ERS-2 SAR subscenes (copyright ESA 2005) obtained on April 27, 2005, north of Philippines in the Luzon Strait. The invisible ship and its wake near the eddy can be tracked easily as shown in the box.

IMPACT/APPLICATIONS

It is clear that these internal wave observations in the South China Seas provide a unique resource for addressing a wide range of processes (Liang et al., 1995; Liu et al., 1996, 1998b; Hsu and Liu, 2000). These processes are listed as follows: the generation of elevation internal waves by upwelling, the evolution of nonlinear depression waves through the critical depth, the disintegration of solitons into internal wave packets, internal wave breaking induced by solitons, the generation of mode-two internal waves, and internal wave-wave interaction. The inclusion of these physical processes is essential to improve quantitative understanding of the coastal dynamics.

RELATED PROJECTS

None

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